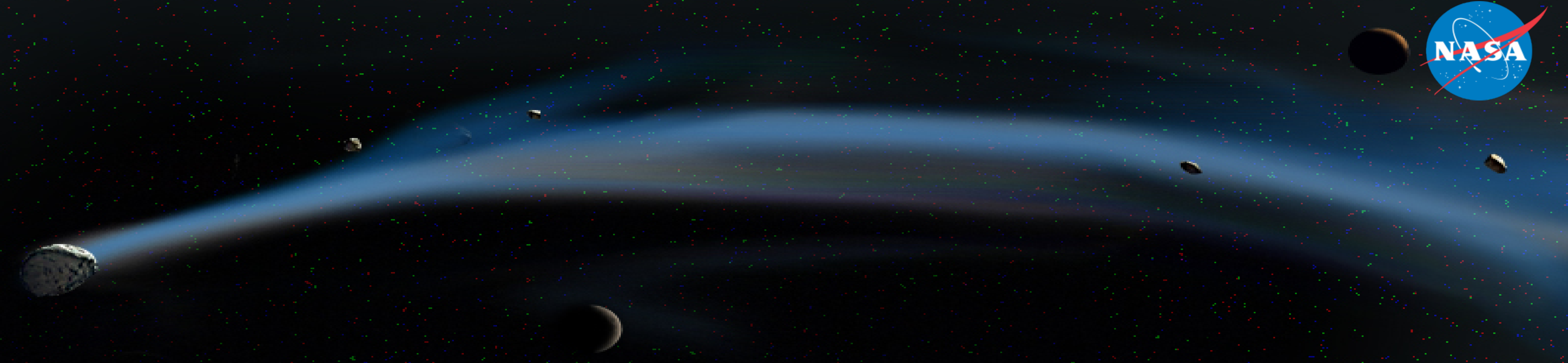

Designing for Outer Space: Design and Evaluation Methods for NASA's Next Generation Space Suit

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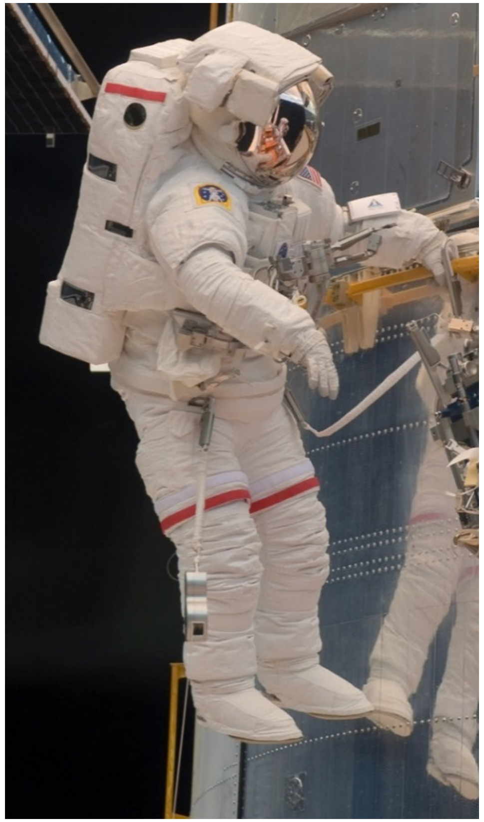
Role of the Space Suit

- Protects astronaut from hazards during various phases of mission
- Launch/Entry Space Suit
  - Normally unpressurized
  - Pressurizes if spacecraft loses cabin pressure
  - Some mobility is required when suit is pressurized in emergency scenario
  - Provides additional protection against:
    - No breathable atmosphere
    - Toxic substances
- Extra-Vehicular Activity (EVA) Space Suit
  - Used to perform spacewalks
  - Normally pressurized
  - Pressurized mobility is required when astronaut performs EVAs
  - Provides additional protection against:
    - No breathable atmosphere
    - Micrometeoroids
    - Thermal extremes
    - Radiation

Launch/Entry Space Suit



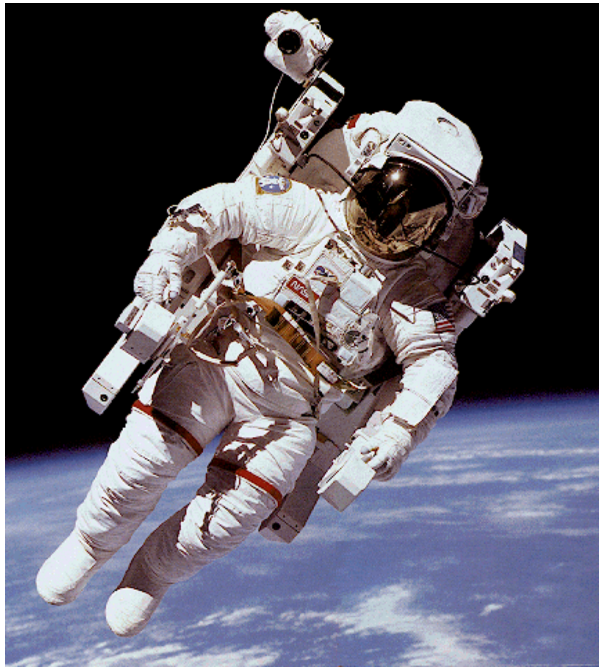
EVA Space Suit

History of Space Suits

Apollo Space Suit

Shuttle ACES Space Suit

Shuttle/ISS EMU Space Suit



1960s 1980s 1990s

Z-2 Space Suit

- Z-2 space suit is NASA's newest prototype, micro-gravity and planetary walking suit
- Z-2 is a part of a development effort to build a suit for NASA missions in low-earth orbit (micro-gravity) and on Mars or other planetary surfaces
- Culmination of knowledge from 20 years of space suit research and development
- Flight-like version of Z-2 will be constructed after Z-2 has been extensively evaluated in various environments (lab environment, micro-gravity environment)

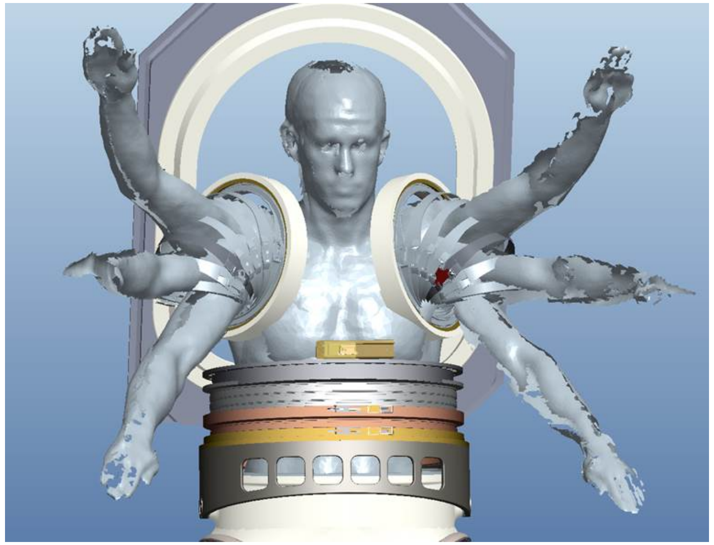
Z-2 Space Suit

Z-2 Space Suit Development

- Goal of project was to validate pressure garment mobility architecture and sizing approach for smaller sized crew
- Design of upper torso was meant to address most common complaints about the current EMU space suit
    - Lack of overhead mobility
    - Reduced work envelope for those with short arms and/or narrow shoulders
    - Reduced visibility for those with shorter torsos
    - Contact with shoulder bearings during task completion
- Budget and schedule only permitted single build of upper torso
    - Anthropometric requirements reduced to target smaller range
    - Selected specific maximum and minimums based off anthropometries of identified crew and engineering test subjects

Z-2 Space Suit Development – Sizing

- Suit sizing is critical to the performance of the suit
- A bad suit fit can lead to injuries or poor suit performance
- Z-2 is first use of 3-D human laser scans and 3-D printed hardware for suit development and sizing
- Used 3-D computer models to perform digital fit checks with body scans of test subjects
- Created a 3-D printed prototype to validate models



Z-2 Computer Model Fit Check

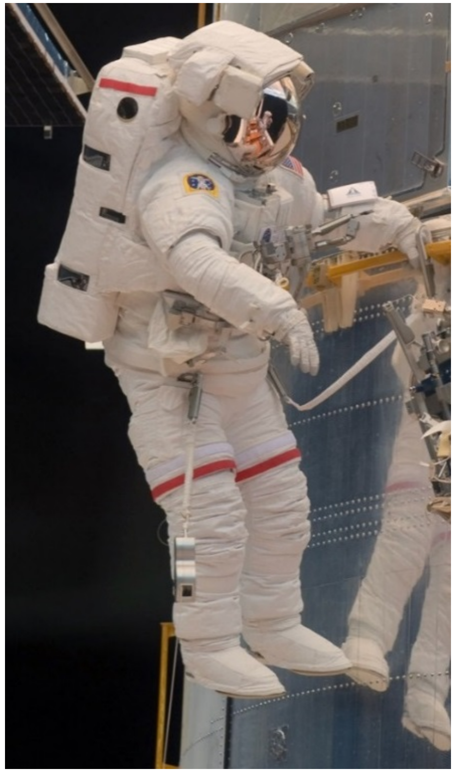
3-D Printed Z-2 Suit

How does NASA evaluate space suits?

- Space suit evaluations consist of unmanned and manned tests
  - Unmanned Tests
    - Joint cycle testing
    - Joint torque testing
    - Environmental testing (radiation, dust, thermal, sharp edges, etc.)
  - Manned Tests
    - Joint cycle testing
    - Task evaluations
- A space suit is designed for operation with a human subject, so we ultimately need to understand how a person performs with the suit

Z-2 NBL Testing – Overview

- Unmanned testing occurred during development of Z-2
- Z-2 was designed to enable manned exploration missions in low-earth orbit and beyond, so we needed to do manned testing to evaluate Z-2
    - First envisioned use would be during demonstration of the Deep Space Gateway (DSG) orbiting Earth's moon
- Neutral Buoyancy Laboratory (NBL) provides closest analog to DSG missions
    - Large pool where space suits are made neutrally buoyant to simulate micro-gravity
    - Existing ISS mock-ups submerged in pool for ISS training provide approximation of tasks anticipated for DSG and Mars transit
- Goal of Z-2 NBL Testing: Evaluate performance of Z-2 space suit, relative to the current state-of-the-art space suit (EMU) in a simulated micro-gravity environment



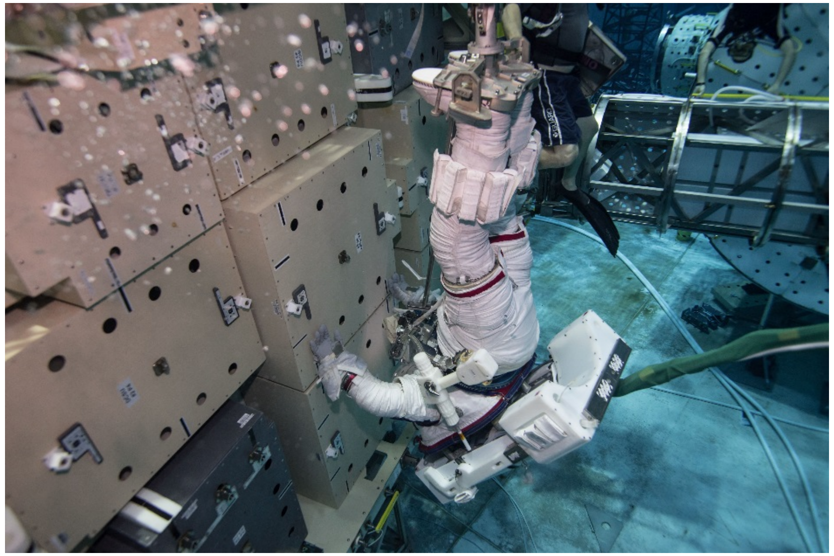
ISS EMU Space Suit

vs.

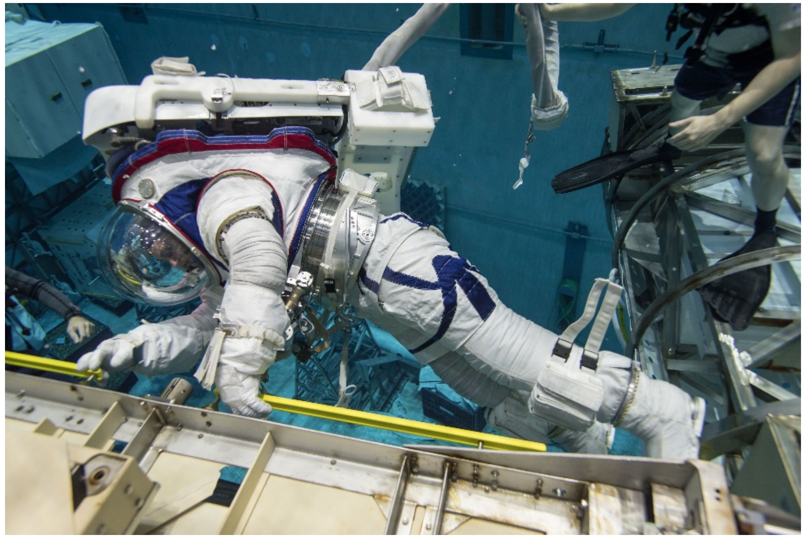
Z-2 Space Suit

Z-2 NBL Testing – Overview

- Z-2 NBL test series consisted of 2 engineering subjects and 5 astronaut subjects (end users)
- 17 evaluations were performed in NBL
- Subjects performed critical tasks that would need to be performed on the International Space Station
- Subjects performed the same tasks in Z-2 and EMU space suit to gain relative comparisons between the space suits



Z-2 Subject Performing Task in NBL



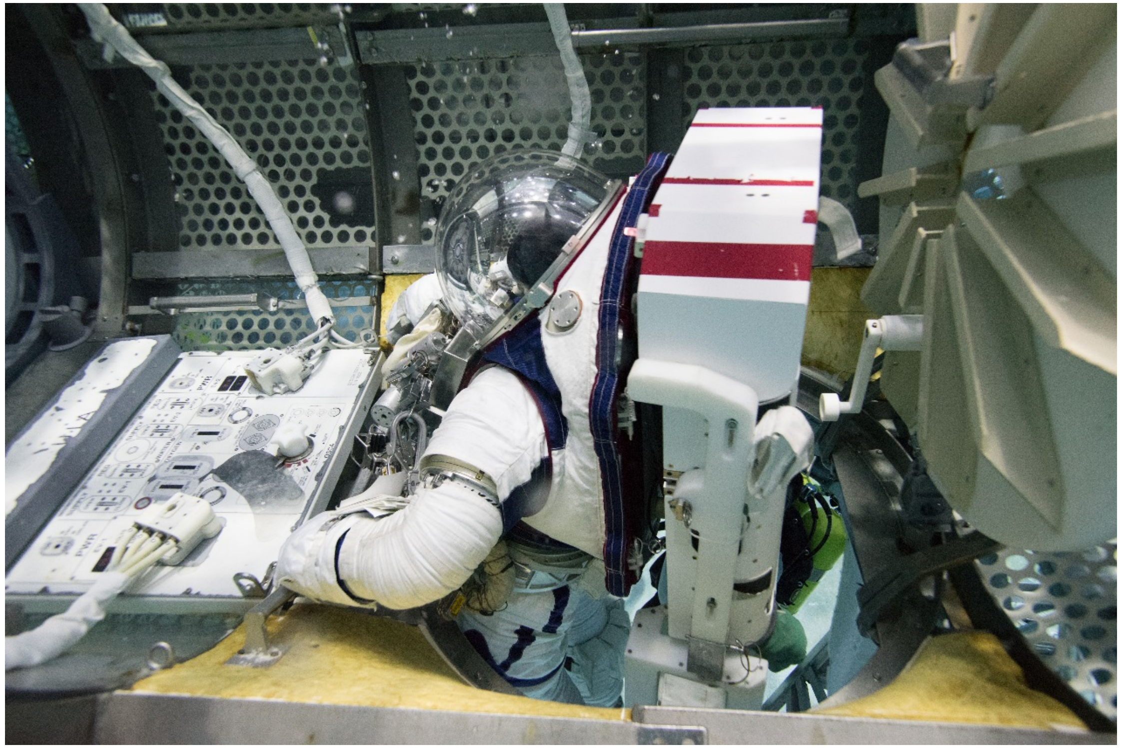
Z-2 Subject Translating in NBL

Space Suit Data Metrics

- A challenge in evaluating space suits with human test subjects is how to obtain objective data
- Subjective feedback from test subjects is the primary data that we collect during suit tests (eg: comments)
  - Advantage: Subjects can provide open-ended responses (responses are not constrained)
  - Disadvantages:
    - Test subject comments can be difficult to interpret
    - Subject may not know how a space suit can be improved – they just want to perform work with minimal effort
    - Subjects may not be able to articulate their comments in a way that engineers can use to improve the design of the suit
    - Comments can be difficult to coalesce to identify trends
- Other evaluation metrics:
  - Rating scales
  - Objective task performance
  - Subject's reach envelope while in space suit
  - Subject’s work rate
  - Life cycle/fatigue of suit components
  - Internal suit forces on human body

Z-2 NBL Testing – Evaluation Metrics

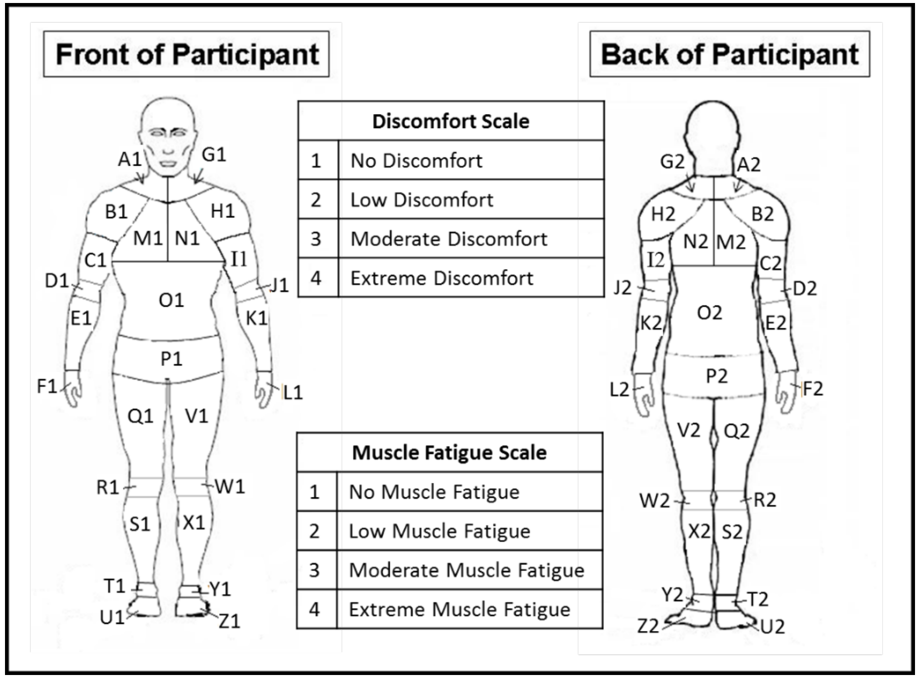
- Subjective Metrics
  - Subject comments
  - Rating scales
- Objective Metrics
  - Objective task performance
  - Subject's subject work rate
  - Subject's reach envelope



Z-2 Subject Ingressing Airlock in NBL

Subjective Data – Rating Scales

- For space suit testing, rating scales are often unique to each test because they are developed to provide specific data to suit engineers
  - Are you trying to determine pass/fail criteria?
  - Are you trying to refine the design of a joint?
  - Are you trying to compare performances of different space suits?
- Rating scales were used to assess: Acceptability, Discomfort, Muscle Fatigue, Exertion, Simulation Quality



Discomfort Scale	
1	No Discomfort
2	Low Discomfort
3	Moderate Discomfort
4	Extreme Discomfort

Muscle Fatigue Scale	
1	No Muscle Fatigue
2	Low Muscle Fatigue
3	Moderate Muscle Fatigue
4	Extreme Muscle Fatigue

Example of Discomfort/Fatigue Scales for Z-2 NBL Testing

- Provides measure of absolute suit performance
- Provides clear delineation between suits
- Easy for test subjects to interpret

Totally Acceptable	Acceptable		Unacceptable	
No improvements necessary	Minor improvements desired	Major improvements desired	Minor improvements required	Major improvements required
1	2	3	4	5

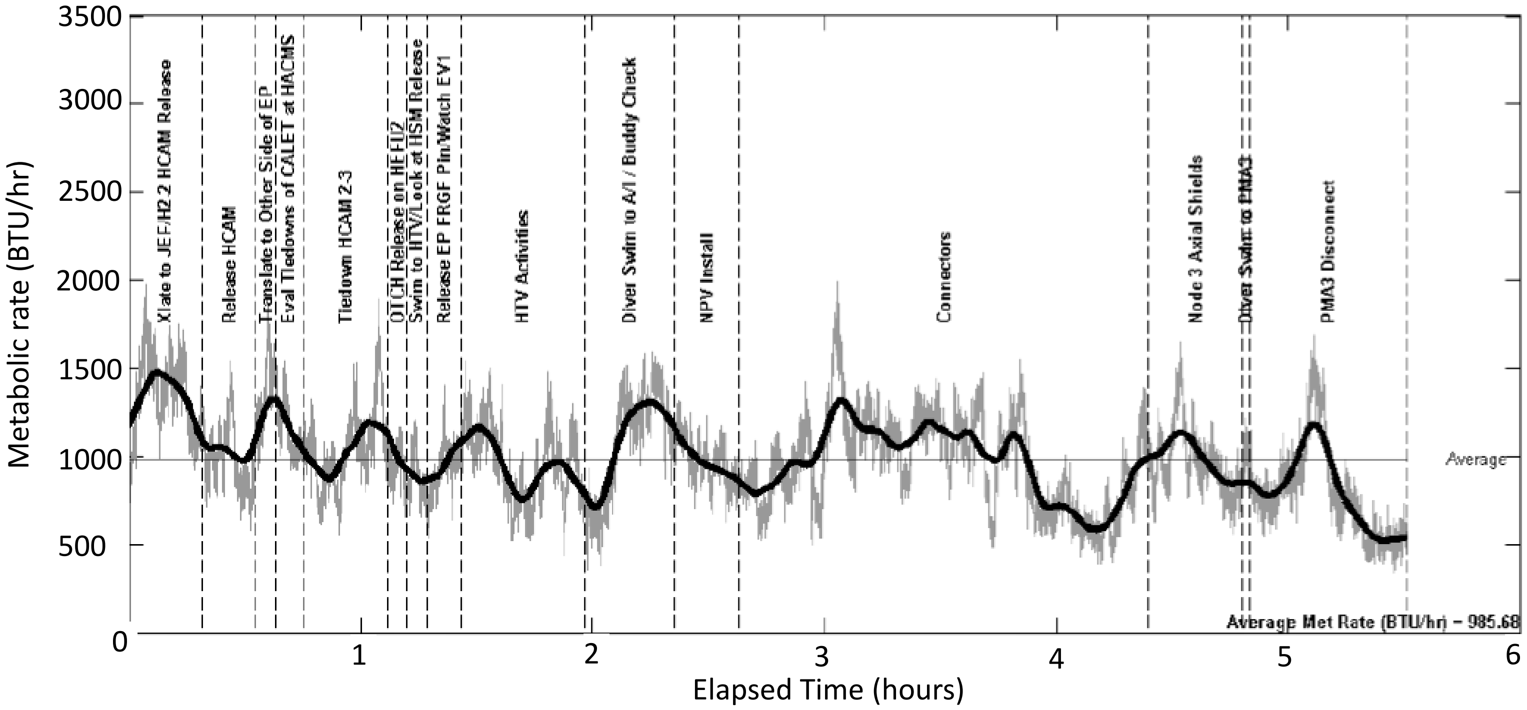
Example of Acceptability Scale for Z-2 NBL Testing

Objective Data – Work Rate

- Subject's work rate provides measure of how hard subject is working inside space suit
- Work rate is correlated to carbon dioxide that is generated by test subject inside space suit

Subject Work Rate ≈ [suit gas flow rate] * [percent of carbon dioxide generated by test subject]

- Test subjects in EMU and Z-2 performed identical tasks



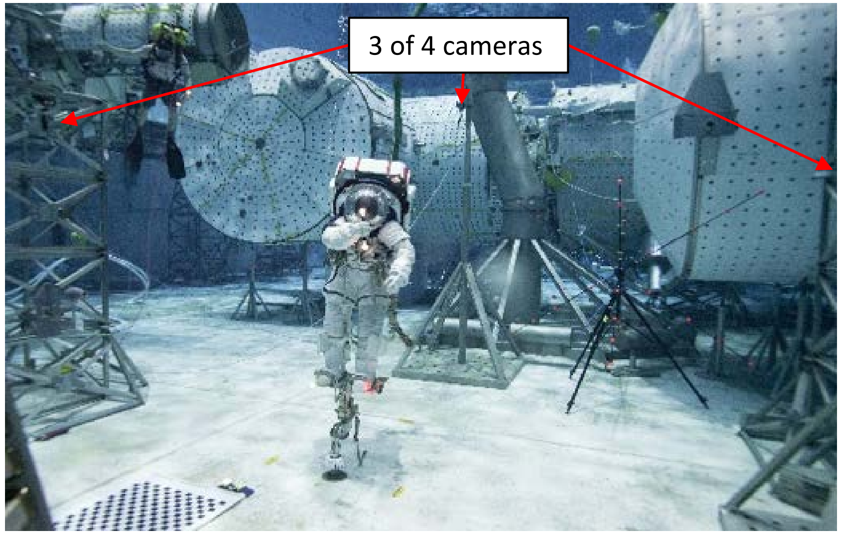
Example of Task-Based Work Rate Data

Objective Data – Work Rate

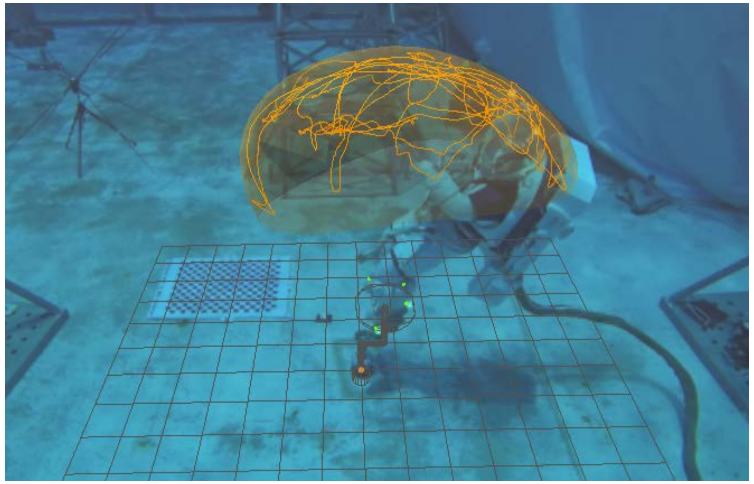
- Advantages
  - Data can be viewed in real time
  - Data is related to on-orbit consumables required for suit
  - Data can help interpret subjective data (acceptability, comfort, etc.)
- Disadvantages
  - Task timelines must be rigidly controlled, which may not be possible for research and development tests
  - Poor simulation quality can adversely affect data

Objective Data – Reach Envelope

- Motion capture is commonly used in laboratory environments to evaluate and compare mobility of different space suits
- Prior to NBL test series, underwater motion capture system for space suits was not available
- Underwater motion capture system was developed for NBL test series
  - Four GoPro cameras
  - Calibration targets
- Subjects performed prescribed motions in space suits to identify all “reachable” areas
- Post-test processing provided digital reach envelopes of Z-2 space suit and EMU space suit
- Metrics derived from motion capture data
  - Reach envelope (where you can reach)
  - Range of motion angles
  - Reach volume



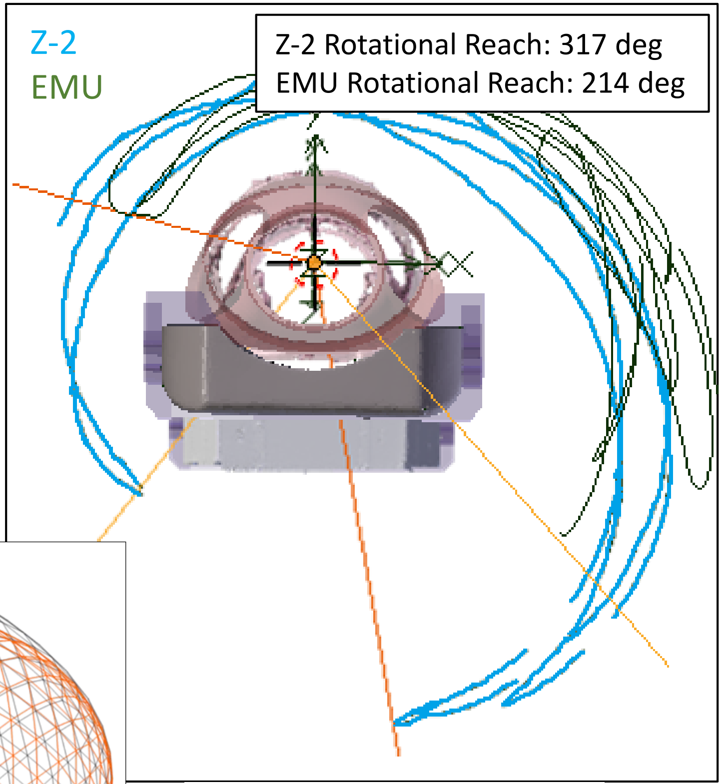
Motion Capture System Test Setup



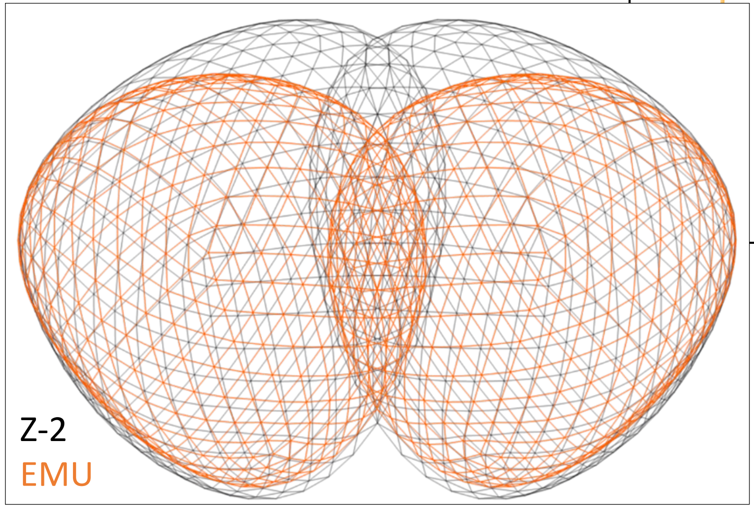
Full Body Reach Envelope

Objective Data – Reach Envelope

- Underwater motion capture system provided quantifiable data for comparing reach of Z-2 and EMU space suits
- Z-2 subjects commented that Z-2 provided better overhead reach and rotational reach than EMU – this was confirmed by motion capture data
- Advantages of System
  - Provides comparative data between suits
  - Enables suit engineers to better understand suit mobility
  - Data can help interpret subjective data (acceptability, comfort, etc.)
- Disadvantages of System
  - Subjects must be fixed to location on pool floor
  - Post-test data processing is time-consuming and labor intensive
  - Data cannot be viewed in real time
  - Motion capture system required periodic re-calibration



Z-2 and EMU Waist Rotation



Z-2 and EMU Cross-Reach

Forward Work

- Complete analysis of Z-2 NBL test data
  - Evaluate motion capture data to better understand mobility differences between Z-2 and EMU space suits
  - Analyze work rate data to quantify energy differences between the suits when performing micro-gravity tasks
  - Assess task performance data to quantify functional capabilities of Z-2 and differences between Z-2 and the EMU
- Use results from Z-2 NBL test series to make design changes to advanced space suit architecture in support of NASA's Deep Space Gateway program

Discussion Topics

- Questions for automotive industry
  - What types of testing does industry perform to evaluate HMI technologies?
  - What metrics does automotive industry consider when evaluating HMI technologies?
  - Does industry primarily rely on objective data or subjective data when evaluating HMI technologies?
  - How does industry evaluate HMI designs with different sizes of people?

Questions?